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Thermo-economic investigation of power generation using micro steam turbines in industrial facilities

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As it is known, steam is used in many industrial facilities. If steam at different pressures is used in processes within the facility, the pressure of the steam must be reduced. A pressure reducer is used to reduce the vapor pressure with conventional methods. Electricity can be generated by removing the pressure reducer and replacing it with a micro steam turbine. Such a system not only allows the production of the heat energy needed by the facility without interruption, but also enables the generation of additional electrical energy in the facility. The aim of this study is to investigate the thermo-economic analysis of such a system. In the analysis, the situation where 5 tons/h of steam is produced at 10 bar pressure and then drops to 5 bar is chosen as the base case. Under these conditions, 44.35 kW electrical power is obtained from the turbine. The internal rate of return and the payback period are calculated as 41.17% and 4 years and 11 months, respectively.

***Keywords**:* *Combined heat and power system, Micro steam turbine, thermo-economic analysis*

1. Introduction

One of the basic requirements of our daily life is energy. With the increasing population both in our country and globally, the need for power is also increasing. Due to increased energy needs, resources are rapidly depleted, the environment is damaged, and countries' dependence on foreign energy rises. This increase in energy need has revealed the issue of ensuring energy supply security. Therefore, alternative energy policies and new technologies should be developed to provide this trust. What is meant by new technologies here is the development of more efficient machinery, equipment, and systems. Along with these developments, energy will be used more efficiently, and it will help reduce greenhouse gas emissions that harm the environment and dependence on foreign energy.

Dinçer and Muslim, conducted a thermodynamic analysis of the Rankine cycle with reheating process. For different system parameters such as boiler temperature, boiler pressure, mass fraction ratio, and net work, the temperature and pressure values were selected between 400 and 590 °C and 10 to 15 MPa, and the energy and exergy efficiencies were examined for 120 cases. When the calculated energy and exergy efficiencies were compared with the actual data and the literature, they saw that the results were close to each other. As a result, they stated that this model is suitable for further increasing plant efficiency [1].

Mago and Luck examined a micro turbine's exhaust waste heat recovery potential (MT) using organic rankine cycle (ORC). With the recovery of waste heat from micro turbine exhaust gases, possible improvements in electricity and exergy efficiencies and specific emissions were determined. During the evaluation, different dry organic working fluids such as R113, R123, R245fa, and R236fa were considered. Overall, they found that using an ORC to recover waste heat from the micro turbine improves combined electrical and exergy efficiencies for all fluids evaluated, with average increases of 27% when using R113 as the working fluid in the ORC. They also found that higher ORC evaporator effectiveness values correspond to lower compression point temperature differences and higher exergy efficiencies. In conclusion, using ORCs to recover waste heat from an MT improves electricity and exergy efficiencies and makes the potential use of MT more affordable by reducing cost, primary energy consumption, and emissions [2].

Masood Ebrahimi et al. have designed a combined cooling, heating, and power cycle running on a micro steam turbine to meet the energy requirements of a residential building. A parametric study is presented to observe the effect of some

parameters, such as turbine inlet pressure and temperature, on the evaluation criteria of the cycle and its components. The exergy analysis revealed that the most incredible exergy destruction occurs in the steam generator in the summer and winter seasons. They have achieved a fuel energy-saving rate of more than 69% in the summer and 25% in the winter. Daily load analyzes have shown that combined cooling, heating, and power cycling can save energy compared to a system that produces cooling, heating, and power separately, except when the required heating load is below 150 kW. In addition, they stated that the total efficiency at the maximum working load in the summer and winter months of the cycle they designed was 25% and 61%, respectively [3].

Yufeng Chen et al. proposed an innovative steam generation system based on recovering low-grade industrial waste hot water. The waste hot water first expels the low-pressure steam and then runs an organic Rankine cycle to compress the low-pressure steam and generate mechanical work. Thermodynamic indicators were calculated under pre-optimization conditions, and a comparative analysis was made between the proposed system and other waste heat utilization systems under the same heat source conditions. Steam production mass ratio, exergy efficiency, and cost per ton of recycled steam under optimized conditions are 2.50%, 44.31%, and $7.67/tonne. When the heat source temperature is 100 °C, the exergy efficiency of the proposed system is 37.01% and 60.59% higher than the steam generation heat pump system and the waste heat power generation system, respectively. In conclusion, this study proposes an efficient and cost-competitive approach to the deep recovery of low-temperature hot water to generate industrial steam [4].

Mago and Luck analyze the potential economic, energetic, and environmental benefits derived from applying a simple micro turbine or combined heat and power cycle system versus a combined micro turbine organic Rankine cycle (MT-ORC). The analysis was carried out for sixteen different geographic locations using 30, 65 and 200 kW micro turbines. They found that the MT-ORC combination is a viable alternative to grid power for some cities where micro turbines alone are not cost-effective. The results also show that for microturbines considered in terms of total electrical power, those with smaller power levels provide the most percentage benefit when combined with an ORC. The total power generated by the MT-ORC system increased by 30%, 26%, and 20% for the 30 kW, 65 kW, and 200 kW micro turbines, respectively. In general, they found that a combined heat and power system is more beneficial when the thermal building requirements are high, and MT-ORC is more useful when there are low thermal requirements [5].

Cetin et al. presented a thermo-economic analysis methodology to calculate the unit energy production cost for a combined cycle system with steam extraction. This methodology aims to find the minimum energy production cost. Therefore, they first saw the minimum electricity generation cost for an electricity-only combined cycle system using the annual leveled cost method. Second, they calculated the minimum heat generation cost for a combined cycle system with steam extraction. The extracted steam causes power loss in the steam turbine and reduces revenue. This is how they determined the cost of heat energy production. In the model, the reduction in income associated with power loss is considered equal to the cost of heat energy, and the cost of heat energy generation is formulated as a function of the cost of electricity generation [6].

When the literature studies are examined, it has been seen that simple micro turbines are not more economical than the electrical energy taken from the grid, considering the installation and operating costs. It has been seen that micro turbines can be made more economical either by using micro turbines as a combined heat and power (CHP) system or by using micro turbines in an organic Rankine cycle.

In this study, the facilities that are using steam at different pressures and pressure reducer, are examined in the meaning of micro steam turbine applicability. A pressure reducer is used to reduce the vapor pressure using conventional methods. Electricity can be generated by replacing the pressure reducer with a micro steam turbine. Such a system ensures the uninterrupted production of the steam needed by the facility and provides the generation of additional electrical power in the facility. This study aims to design such a system and to investigate the applicability of the micro steam turbine by examining it thermodynamically and economically in the combined heat and power system.

2. System description

In this study, a system in which turbine inlet-outlet pressures and steam flow rates are used as variable parameters was created by using micro turbines of different capacities and boiler room equipment of various capacities in a combined heat and power system. As a system management strategy, the system is designed to meet the thermal load in this study. The electricity produced becomes an extra output to be used to partially meet the electricity load of the facility. As the first output, valuable thermal energy is produced in the form of steam, and as the second output, electricity is produced by installing a steam turbine on top of the steam system.

In our proposed system, there is already a steam boiler in the facility to meet the steam needs of the processes, and this steam boiler already produces steam at high pressure compared to the high pressure steam process. It is planned to

produce electricity within the facility by investing only one micro steam turbine in the existing facility. Figure 1 shows the schematic diagram of our proposed system.

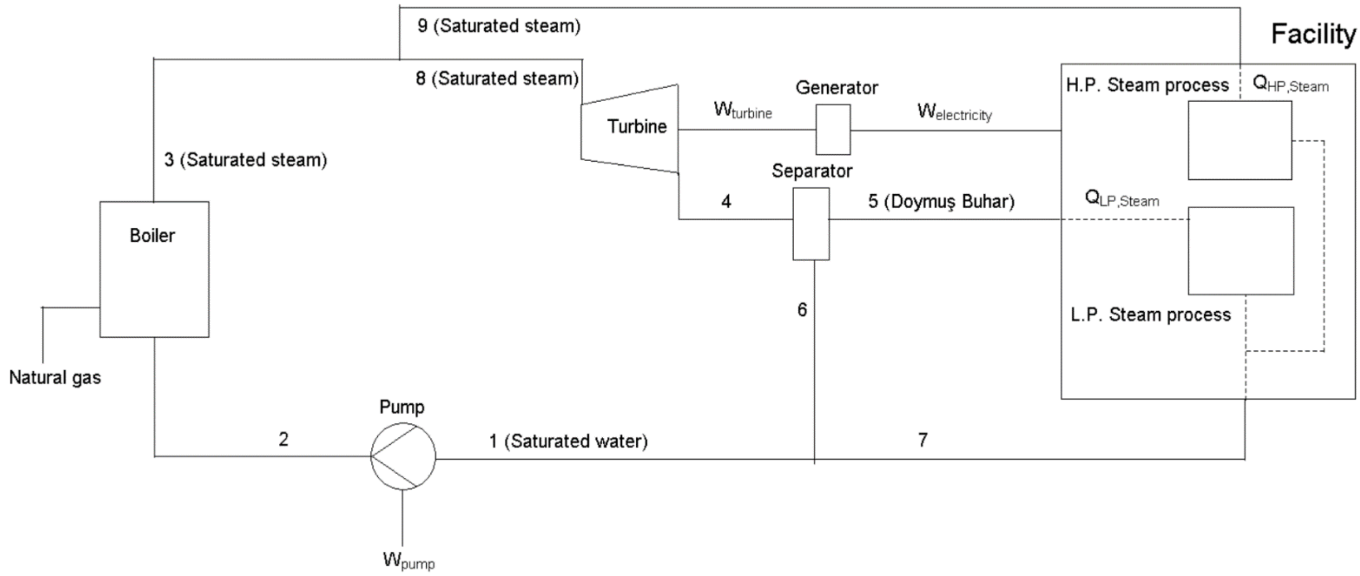

Figure 1. *Schematic diagram for the proposed system.*

As seen from the Figure 1, the working fluid enters the system as saturated water (1). It is pressurized at the desired level with the pump (2). Saturated steam is produced through a steam boiler working with natural gas (3). After state 3, the saturated steam used in high-pressure steam processes is transmitted to the high-pressure steam processes (9). Both extra generating electricity from the turbine and the saturated steam used in low-pressure steam processes are sent to the turbine (8). Some of the steam expands in the turbine and generates work. Additional electrical energy is produced to be used in the facility using the generator connected to the turbine's shaft. The working fluid, which comes out of the turbine as a liquid-steam mixture (4), is separated as liquid and steam utilizing a separator. Liquid part (6) is sent to the pump to complete the cycle. The steam part (5) is sent to low-pressure processes in the facility to be used in low-pressure steam processes. Then, the working fluid from both low pressure and high-pressure steam processes is sent to the pump (7) to complete the cycle.

3. Thermodynamic analyses

The below assumptions are made for thermodynamics analyses:

• Pipelines and pressure losses in the pump are neglected.
• State changes in turbine and pump occur isentropically.
• The flow rate of the water circulating in the system is constant.
• It is assumed that there is no heat transfer between the system components and the outside environment.
• Boiler efficiency, η_{boiler} : 0.85
• Generator efficiency, $\eta_{genarator}$: 0.95
• Pump efficiency, η_{pump} : 0.90
• Steam turbine efficiency, $\eta_{turbine}$: 0.53
• Lower heating value of natural gas, $Hu_{Natural\ gas}$: 34,518 kJ/m^3

A. Mass balance:

According to the conservation of mass principle, the mass balance equation for all components can be expressed as follows in this study.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

B. *Energy balance:*

The first law of thermodynamics is applied to all system components to obtain the energy balance equations for all system components. The general energy equation known from the first law of thermodynamics is shown in equation 2 below.

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out}\left(h_{out} + \frac{1}{2}V_{out} + gz_{out}\right) - \sum \dot{m}_{in}\left(h_{in} + \frac{1}{2}V_{in} + gz_{in}\right) \tag{2}$$

Assuming that the potential and kinetic energies do not change, the general energy equation takes the form of equation 3, shown below.

$$\dot{m}_{in}h_{in} + \dot{Q}_{in} + \dot{W}_{in} = \dot{m}_{out}h_{out} + \dot{Q}_{out} + \dot{W}_{out} \tag{3}$$

The energy balance for each component can be denoted as follows:

- Pump

$$\dot{m}_1 h_1 + \dot{W}_{pump} = \dot{m}_2 h_2 \tag{4}$$

- Boiler

$$\dot{m}_2 h_2 + \dot{Q}_{boiler} = \dot{m}_3 h_3 \tag{5}$$

- Turbine

$$\dot{W}_{turbine} = \eta_{turbine}(\dot{m}_8 h_8 - \dot{m}_4 h_4) \tag{6}$$

- Separator

Since there is no energy production or consumption in the separator, there is no need to write the energy balance equation. The separator is only used to separate the steam and liquid from the saturated liquid-steam mixture at the turbine outlet.

- Facility

$$\dot{Q}_{LP,steam} = \dot{m}_5 h_5 \tag{7}$$

$$\dot{Q}_{HP,steam} = \dot{m}_9 h_9 \tag{8}$$

$$\dot{W}_{electricity} = \eta_{generator}(\dot{W}_{turbine} - \dot{W}_{pump}) \tag{9}$$

3. Economic analyses

Only a steam turbine investment is required to establish the proposed system in the facility because there is already a natural gas boiler in the facility that meets the steam needs of the existing processes. In this study, 5 tons/h steam is produced at 10 bar pressure in the boiler. It is assumed that steam enters high-pressure processes at 10 bar and low-pressure processes at 5 bar. Therefore, the turbine inlet pressure is 10 bar, and the turbine outlet pressure is 5 bar. The following assumptions are made for the calculations under these conditions:

• The economic life of the proposed system is assumed to be 25 years.
• The annual operating time of the system is assumed to be 8,760 hours.
• The initial investment cost of a 100 kW turbine is 190,000 €, and the operation and maintenance cost is 5,000 €/year.
• Discount rate, i : 20%

• Escalation rate, e : 15%
• The price of electricity from the grid, $C_{electricity}$: 0.14160 €

Net present value (NPV) calculations were made using equation (10) :

$$NPV = \sum_{t=0}^{n} \frac{B(t)-C(t)}{(1+i)^t} \tag{10}$$

Where:

• B(t)= Their income at the end of period t.
• C(t)= Expenses at the end of period t.
• The annual operating time of the system is assumed to be 8,760 hours.

The internal rate of return can be defined as the discount rate that makes the present value of net profit zero in a given period. If the internal rate of return is represented by IRR, equation (10) is set to zero, and IRR can be found by equation (11) as follows:

$$NPV = \sum_{t=0}^{n} \frac{B(t)-C(t)}{(1+IRR)^t} = 0 \tag{11}$$

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period. In contrast, the internal rate of return (IRR) is a calculation used to estimate the profitability of potential investments. These expressions are mainly used to evaluate whether a new investment opportunity is viable.

4. Results and discussions

The proposed system's thermodynamic and economic analyses were made for the whole system. Table 1 shows the assumed and calculated thermodynamic properties for all state points. Under these conditions, it is estimated that an additional 44.35 kW of electrical power can be obtained. At the same time, the steam needed by the processes using steam in the facility continues to be met. In other words, this is an indication that 1,064 kWh of electrical energy can be produced at the facility in one day, instead of being taken from the grid, without any extra fuel consumption.

Table 1. *Some thermodynamic properties for different points.*

No	P (kPa)	T (°C)	h (kJ/kg)	ṁ (kg/s)	s (kJ/kg·°C)	x
1	500	151.8	640.1	1.389	1.86	0
2	1,000	151.9	640.6	1.389	1.86	0
3	1,000	179.9	2,777	1.389	6.585	1
4	500	151.8	2,648	0.6944	6.585	0.9525
5	500	151.8	2,748	0.6615	6.821	1
6	500	151.8	640.1	0.03299	1.86	0
7	500	151.8	640.1	1.356	1.86	0
8	1,000	179.9	2,777	0.6944	6.585	1
9	1,000	179.9	2,777	0.6944	6.585	1

In Table 2, incomes and expenses are shown according to the years due to the economic analysis. As can be seen in the table, as a result of the implementation of such a system under the thermodynamic conditions mentioned in the previous section, it is seen that the total revenues began to exceed the total expenses within the 4th year.

Table 2. *Cash flows by year.*

t	Investment cost(€)	O&M cost(€)	Saving cost of electricity(€)	(1+i)^t	Present value of the cost of savings(€)	Present value of expenses(€)	Net profit(€)	Present value of net profit(€)	Cumulative NPV(€)
0	190,000			1.0000		190,000	- 190,000	- 190,000	- 190,000
1		5,000	55,015	0.8333	45,846	4,167	50,015	41,679	- 148,321
2		5,750	63,267	0.6944	43,935	3,993	57,517	39,942	- 108,379
3		6,613	72,757	0.5787	42,105	3,827	66,144	38,278	- 70,101
4		7,604	83,670	0.4823	40,350	3,667	76,066	36,683	- 33,418
5		8,745	96,221	0.4019	38,669	3,514	87,476	35,155	1,737
6		10,057	110,654	0.3349	37,058	3,368	100,597	33,690	35,427
7		11,565	127,252	0.2791	35,514	3,228	115,687	32,286	67,713
8		13,300	146,340	0.2326	34,034	3,093	133,040	30,941	98,654
9		15,295	168,291	0.1938	32,616	2,964	152,996	29,652	128,305
10		17,589	193,535	0.1615	31,257	2,841	175,945	28,416	156,721
11		20,228	222,565	0.1346	29,955	2,722	202,337	27,232	183,954
12		23,262	255,950	0.1122	28,706	2,609	232,688	26,097	210,051
13		26,751	294,342	0.0935	27,510	2,500	267,591	25,010	235,061
14		30,764	338,493	0.0779	26,364	2,396	307,730	23,968	259,029
15		35,379	389,267	0.0649	25,266	2,296	353,889	22,969	281,998
16		40,685	447,658	0.0541	24,213	2,201	406,972	22,012	304,011
17		46,788	514,806	0.0451	23,204	2,109	468,018	21,095	325,106
18		53,806	592,027	0.0376	22,237	2,021	538,221	20,216	345,322
19		61,877	680,831	0.0313	21,311	1,937	618,954	19,374	364,696
20		71,159	782,956	0.0261	20,423	1,856	711,797	18,567	383,262
21		81,833	900,399	0.0217	19,572	1,779	818,567	17,793	401,055
22		94,108	1,035,459	0.0181	18,756	1,705	941,352	17,052	418,107
23		108,224	1,190,778	0.0151	17,975	1,634	1,082,554	16,341	434,448
24		124,457	1,369,395	0.0126	17,226	1,566	1,244,938	15,660	450,108
25		143,126	1,574,804	0.0105	16,508	1,500	1,431,678	15,008	465,116

The values calculated by the net present value and internal rate of return methods and the evaluation of the investment are given in Table 3.

Table 3. *Economical findings.*

NPV	465,116 €
IRR	41.17%
Payback Period	4 years 11 months

As seen in Table 3, the internal yield rate was 41.17%. While calculating the cost, we calculated the discount rate currently used in the market as 20%. The discount rate represents the rate of return we expect from this investment. As a result of our calculations, the IRR is 41.17%, indicating that this investment will yield more profit than expected. However, if there is a profit expectation above 41.17% from this investment, it indicates that this investment will not be profitable. In addition, the net present value of this investment is €465,116 according to the net present value method, which considers the time value of money over the 25-year life of the investment. This shows that when we evaluate the investment according to the net present value method, we will profit € 465,116 at the expected rate of return at the end of the investment's life.

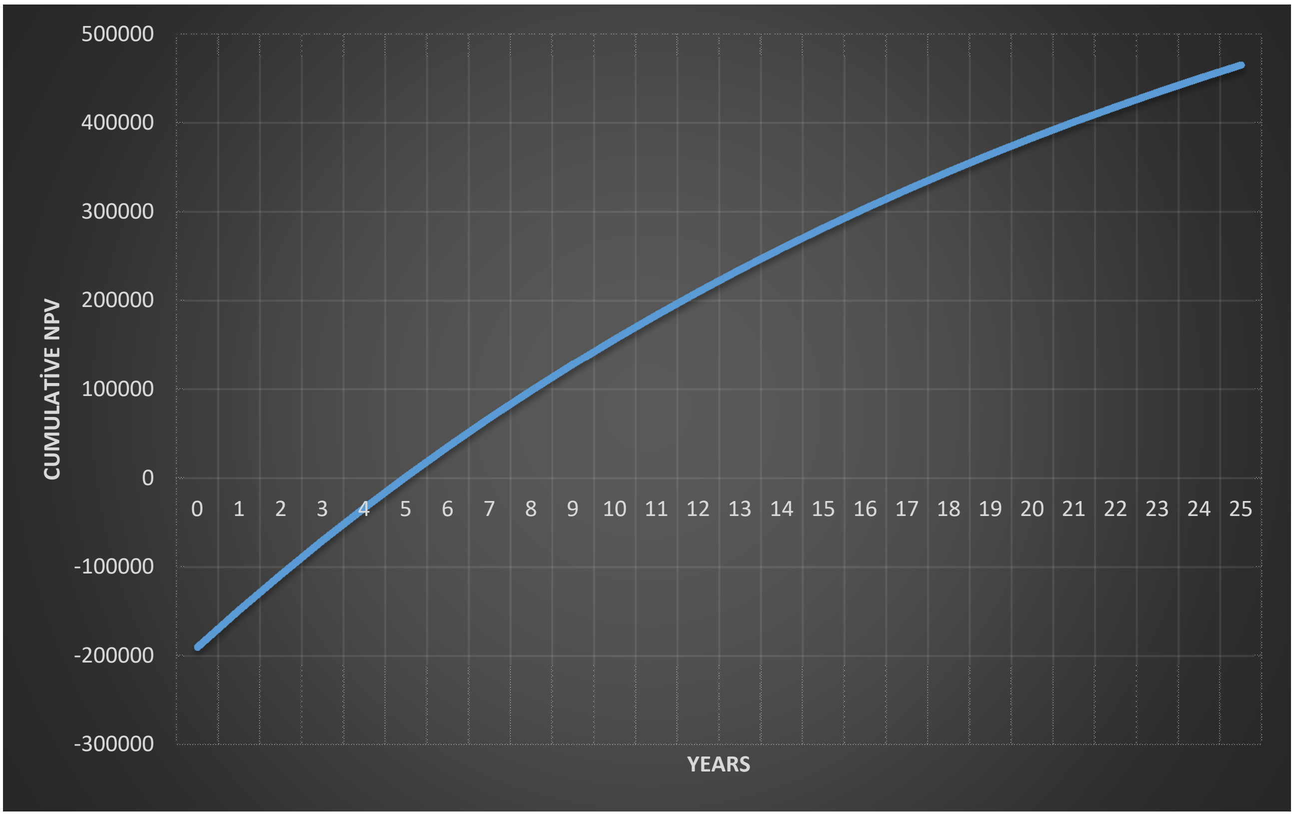

Figure 2. NPV changes by years.

As seen in Figure 2, the payback period of the investment was found to be 4 years and 11 months. Considering that the investment has a life of 25 years, it can be considered that the investment will be appropriate in the medium term.

3. Conclusion

In this study, the suitability of micro steam turbines for plants that use steam at different pressures and use a pressure reducer for pressure adjustment was evaluated. Provided that the existing steam boiler and the steam process remain the same, the installation of a micro turbine instead of a steam pressure reducer and the thermo-economic situation that will occur due to this have been studied. The micro turbine will be able to provide additional electricity generation that the plant can use.

In a case study conducted for a plant using steam at pressures of 10 bar and 5 bar, it was calculated that an electrical power of 44.35 kW can be obtained in the case of the use of a micro turbine. On the other hand, in the economic analysis conducted, it was determined that a possible investment to be made can pay for itself in less than 5 years, and the IRR value will be about 41%. According to the results obtained, it shows that micro steam turbines can be used for plants using a steam pressure reducer, which can give both technically and economically favorable results.

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